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RESISTANCE OF CONCRETE MASONRY WALLS WITH MEMBRANE CATCHER SYSTEMS SUBJECTED TO BLAST LOADING

(PREPRINT)

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Resistance of Concrete Masonry Walls with Membrane Catcher Systems Subjected to Blast Loading

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ABSTRACT

This paper describes a methodology for analyzing the impulse pressure response of unreinforced concrete masonry walls that have been retrofitted with membranes that are not bonded to the masonry (catcher systems). Membrane catcher systems can be used to protect building occupants from secondary debris resulting from blast pressure, and the effectiveness of systems comprising polymers, composites, geotextiles, and thin steel and aluminum sheets has been researched extensively over the past fifteen years. The methodology presented herein is based upon the large displacement response of the unreinforced masonry wall, with and without compression membrane arching, and the subsequent tension membrane resistance of the catcher system. The necessary equations are developed in the form of nonlinear resistance functions, which are then used in single-degree-of-freedom analyses to develop dynamic response predictions. The applicability of the approach is substantiated through comparison to full-scale blast test results, and demonstrations involving disparate materials and loading are made.

1. BACKGROUND AND INTRODUCTION

Unreinforced, ungrouted, concrete masonry unit (CMU) walls, one of the most cost-efficient and effective methods of constructing infill exterior walls of buildings, are used extensively worldwide. However, unreinforced masonry (URM) walls are extremely vulnerable to fragmentation under blast impulse loads, potentially resulting in severe injury to occupants. For these reasons, the United States (US) Department of Defense (DoD) Antiterrorism/Force Protection Construction Standards [1] prohibit the use of unreinforced CMU exterior walls for construction of new DoD facilities. Although URM walls are no longer permitted for new DoD construction, there exist worldwide many buildings and facilities constructed of unreinforced exterior CMU walls that might be considered high risk, as well as industrial facilities that could be subjected to an accidental explosion. Therefore, over the past

several decades the US government has encouraged and sponsored research toward developing cost-efficient construction approaches for retrofitting existing masonry structures.

An extensive array of retrofit materials and testing methods has been employed during masonry resistance investigations. Both the earthquake and blast research communities have researched this area extensively, beginning in the 1980s. Blast retrofit research programs tend to focus exclusively on out-of-plane flexural response, whereas earthquake research programs must consider both the out-of-plane flexure and in-plane shear resistances. Since the mid-1990s, research has focused on the use of fiber-reinforced polymers (FRP) due to advantages such as strength-to-weight ratio, workability, and corrosion resistance, although the effectiveness of sheet metals (aluminum and steel) has also been demonstrated. Furthermore, there is an enormous variety of commercially available products that could potentially be used for the URM retrofit application. For DoD applications outside the continental US, weight, transportability (minimum transport volume), and installation ease typically determine the practicability of a given retrofit approach. This is especially true of in-theatre requirements. A state-of-the-art review of FRP composites and polymers used to strengthen concrete and masonry structures for blast resistance was published by Buchan and Chen in 2007 [2]. An engineering technical letter entitled "Airblast Protection Retrofit for Unreinforced Concrete Masonry Walls" was published in 2000 and another published in 2002 entitled "Airblast Protection Polymer Retrofit of Unreinforced Concrete Masonry Walls" that provides guidance on specific installation procedures [3, 4].

Under the blast impulse load scenario, the primary masonry retrofit challenge is to provide an easy-to-install membrane system on the inside (side opposite the explosion's origin) surface of the masonry that provides significant ductility and strain energy absorption capacity to capture the fragments as the brittle masonry wall structure undergoes large transient displacements. Initially, relatively stiff composite laminates and geotextiles were investigated, including glass, carbon, and aramid fiber reinforced polymers. While these composites were able to control the out-of-plane dynamic displacement resulting from blast loading, the resulting connection forces were relatively large due to the rigidity of these materials. Some of these materials were "bonded" to the inside surface of the masonry wall using commercially available epoxies, while others were installed without any direct connection to the masonry, thereby acting as a "catcher system" that simply provides a boundary that restrains secondary fragmentation of the masonry. In 1999, the Airbase Technologies Division of the Air Force Research Laboratory demonstrated an alternate concept—retrofits comprising a thin membrane of neat (no fiber reinforcement) sprayed-on polymers. The early versions of this approach were a polyurea-based coating similar to that used for truck bed liners [5, 6]. Water-based trowel-on polymers were subsequently developed to circumvent the volatile organic compound detractions associated with the initial spray-on products. Therefore, two mechanically disparate retrofit approaches evolved: "catcher membrane" and "fully bonded."

Although the overall life-safety objective is the same and there is some overlap in materials used, there are significant differences in the mechanisms by which these two approaches attenuate the strain energy resulting from blast load. The catcher membrane approach results in a relatively uniform distribution of strain over the membrane height, and generally a lower magnitude of maximum strains for a given level of effectiveness. This implies that (1) it is not necessary that the materials used have extremely large strain ability, (2) the total resistance provided is a relatively simple superposition of the flexural resistance provided by the masonry and large displacement resistance provided by the membrane retrofit, and (3) the entire internal force within the membrane retrofit is reacted by connections to the host structure (floor and ceiling). Under transient loading, these reaction forces are

proportional to the rigidity of the retrofit membrane, and very robust, perhaps expensive, connections must be designed and constructed. The fully bonded approach assumes that the bond between the retrofit membrane is stronger than the modulus of rupture of the masonry concrete and the tension strength of the retrofit material, and therefore results in highly localized strains at locations where the wall cracks in tension (typically along the bed joints). This implies that a bonded retrofit material must have a higher strain capacity to preclude tearing along mortar joint cracks as the wall flexes inward. The other challenge associated with the fully bonded retrofit approach is that the large displacement resistance required for engineering analyses depends on the strain length that occurs, which in turn depends upon the tension rigidity of the retrofit material. A potential advantage of the fully-bonded approach, however, is that it minimizes connection force demands; testing on low-stiffness, high-elongation sprayed-on polymer URM retrofits have demonstrated that extending the material to the host structure at floor and roof boundaries may be sufficient, and that mechanical connections may not be required for the fully bonded approach [5, 6].

Most of the literature reported in the public domain on the performance of masonry retrofits subjected to blast loads has been qualitative and lacking in the rigorous engineering methodology needed to properly design masonry retrofit systems. As much blast design is based upon single-degree-of-freedom (SDOF) methodology, a recent emphasis has been placed on developing the resistance required for SDOF input. In one of the earliest reports, Slawson et al. [7] described the use of commercially available geofabrics that were used to retrofit concrete masonry unit walls exposed to blast pressure. SDOF and finite element models were used in an attempt to correlate to test results. The geofabrics were successful in preventing debris from entering the interior of the test structure. Six wall panel models were generated using the Wall Analysis Code [8] SDOF software and the DYNA-3D finite element software. Each wall panel model was 3.05 m wide and 2.64 m tall. For both the WAC and DYNA-3D models, there was one control wall and two walls that were retrofitted with the anchored fabric. The membrane resistance of the anchored fabric was added to the resistance function of the WAC-generated wall panels to account for the retrofit. The finite element models contained over 80,000 solid elements, and a 40 x 40 mesh of linear-elastic membrane elements placed 3 mm behind the wall that represented the anchored geofabric. Results from the WAC and DYNA-3D models were compared to the data collected from the validation tests. The results from the models did not correlate well with the results from the explosive tests. It was recommended that additional experimental data would be required to fully validate the computation procedures. Other researchers at the US Army Engineer Research and Development Center subsequently conducted extensive experimental and analytical investigations of bonded and non-bonded CMU wall retrofits [9, 10, 11].

With similar objectives as the work presented herein, Salim et al. [12, 13] presented resistance functions derived from static load experiments of several different membrane retrofit materials. The resistances included the flexibility of the anchors and connections used to connect membrane retrofit to the floor and roof of host structures. A blast retrofit design example was presented. The details of the testing and analytical approach were expanded, along with brief comparisons to full-scale explosion tests, in Fitzmaurice et al. [14].

This paper therefore presents the development of a methodology for calculating impulse pressure response of unreinforced concrete masonry walls retrofitted with membrane catcher systems, including large-displacement resistance and compression arching effects. This presentation follows two recent papers by Moradi et al. [15, 16] that presented robust large-deflection analytical resistance definitions for bonded retrofit walls, with and without arching effects. In the present paper, the membrane catcher system is assumed to be attached to the host structure at the top and bottom (floor and ceiling), and

may be made of thin steel or aluminum, neat polymeric sheets, or composite laminates. The resistance functions were incorporated into SDOF algorithms, and the accuracy and applicability of the developed analytical methodology demonstrated through correlation to full-scale explosion tests involving a wide range of design, geometry, and material characteristics.

2. RESISTANCE FUNCTION DEVELOPMENT

The unreinforced concrete masonry wall with a membrane catcher system resists blast pressure in two distinct phases of resistance. The first phase is dominated by the flexural resistance provided by the concrete masonry; the concrete masonry wall undergoes the initial elastic response, the subsequent initiation of cracks, and nonlinear rocking response (Figure 1). The resistance of the unreinforced concrete masonry wall is considered for no-arching cases (Figure 2) and with arching effects (Figure 3). In the second phase, the catcher system responds through large-displacement membrane action until failure, which may be governed by the ultimate strain of the retrofit material or system instability due to excessive displacement. Each resistance phase is examined separately and deflection-versus-pressure equations are developed. The final resistance function of the system is the superposition of the two resistance phases.

2.1 Unreinforced Concrete Masonry Wall — No Arching

The equations that define the resistance of unreinforced concrete masonry walls without arching effect were presented by Moradi et al. [15]. The horizontal reaction H and the internal vertical reaction R, illustrated in Figure 2, and the resistance function in terms of Δ versus pressure p are summarized here.

$$H = \frac{ph}{2} + \frac{W_i \Delta}{2h} \tag{1}$$

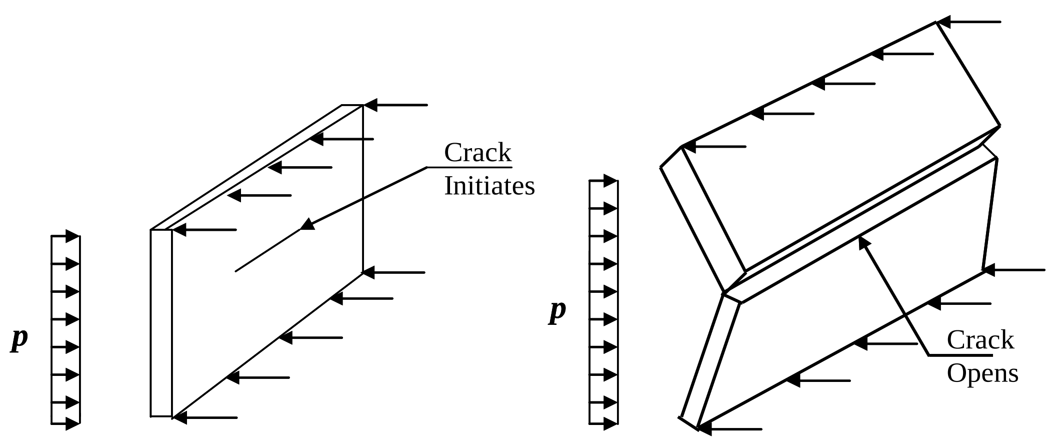

Figure 1. Unreinforced masonry wall spanning vertically and subjected to lateral load

$$R = \frac{W_i}{2} + P \tag{2}$$

$$\Delta = \frac{t}{6} + \frac{y}{3} - \frac{(3-2\alpha)\,ph^2}{12W_i + 24P} \tag{3}$$

Where p is the lateral pressure, h is the height of the wall, W_i is the weight of the wall, t is the wall thickness, Δ is the lateral displacement at the height-wise center of the wall, y is the crack depth through the thickness, and α is the degree of fixity at the supports. The elastic deflection of the wall prior to crack is calculated using Eq. (4). Prior to crack, the top and bottom interfaces of the unreinforced masonry wall are assumed to be fully fixed. Eq. (4) accounts for partial end fixities (α) of the top and bottom interfaces of the unreinforced concrete masonry wall after the development of cracks.

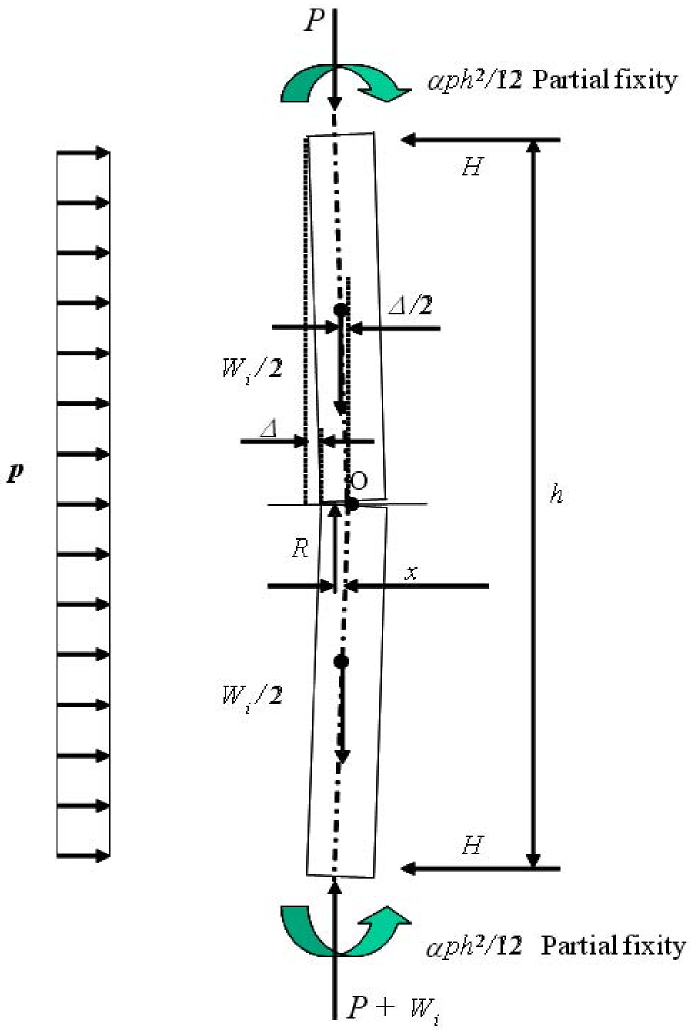

Figure 2. Free-body diagram of the unreinforced concrete masonry wall without arching

$$\Delta_{\max.elastic} = \frac{(5-4\alpha)\, ph^4}{384 E_c I_g} \tag{4}$$

Where E_c is the concrete masonry elastic modulus and I_g is the gross (uncracked) moment of inertia. Moradi et al. [15] assumed that the displacement Δ increases in proportion with the central curvature of the wall, hence:

$$\Delta_{crG} = \beta\, \Delta_{cr} \tag{5}$$

Where Δ_{cr} is the deflection at the onset of cracking, Δ_{crG} is the deflection as crack grows, and β is the curvature ratio [15]. The resistance function can now be developed in an iterative fashion. At the onset of crack (y=0), the problem is reduced to two equations (Eqs. (3) and (4)) and two unknowns (Δ and p). As crack grows (y>0), Δ is calculated using Eq. (5), and p is subsequently calculated using Eq. (3). When this process is programmed for small increments of y, the result defines the full resistance of the unreinforced concrete masonry wall without arching effects.

2.2 Unreinforced Concrete Masonry Wall with Arching

The resistance equations can also be developed to include compression arching effects [15]:

$$H_{\mathrm{Top}} = \frac{ph}{2} - (P + W_i)\left(\frac{t-a}{2h}\right) + \frac{W_i \Delta}{2h} \tag{6}$$

$$H_{\mathrm{Bottom}} = \frac{ph}{2} + (P + W_i)\left(\frac{t-a}{2h}\right) - \frac{W_i \Delta}{2h} \tag{7}$$

$$R = P + V_{\mathrm{Top}} + \frac{W_i}{2} \tag{8}$$

$$p = -\frac{8}{h^2}\left(P\left(\frac{t-a}{2}\right) + \frac{W_i}{2}\left(\frac{t-a}{2} - \frac{\Delta}{2}\right) - \left(P + V_{Top} + \frac{W_i}{2}\right)\left(x + \frac{t-a}{2} - \Delta\right)\right) \tag{9}$$

Where a is width of arching compression area, R is the resultant force of the compressive stresses in the wall, V_{Top} is the arching force at the top support, x is the distance from R to the wall centerline, and all other symbols are the same as have been previously defined. Before crack initiation at y = 0, it is safe to assume that arching forces are zero and Eq. (10) is derived from the equations of moment and force equilibrium:

$$\Delta = \frac{\left(P + \frac{W_i}{2}\right)\left(\frac{t}{6}\right) - \frac{ph^2}{8}}{P + \frac{W_i}{4}} \tag{10}$$

When y = 0, the wall exhibits elastic bending and its deflection may also be calculated from the following equation for a fixed end beam:

$$\Delta = \frac{ph^4}{384E_c I_g} \tag{11}$$

Eq. 12 is derived from Eqs. (10) and (11) and calculates the pressure at y = 0, and subsequently Δ:

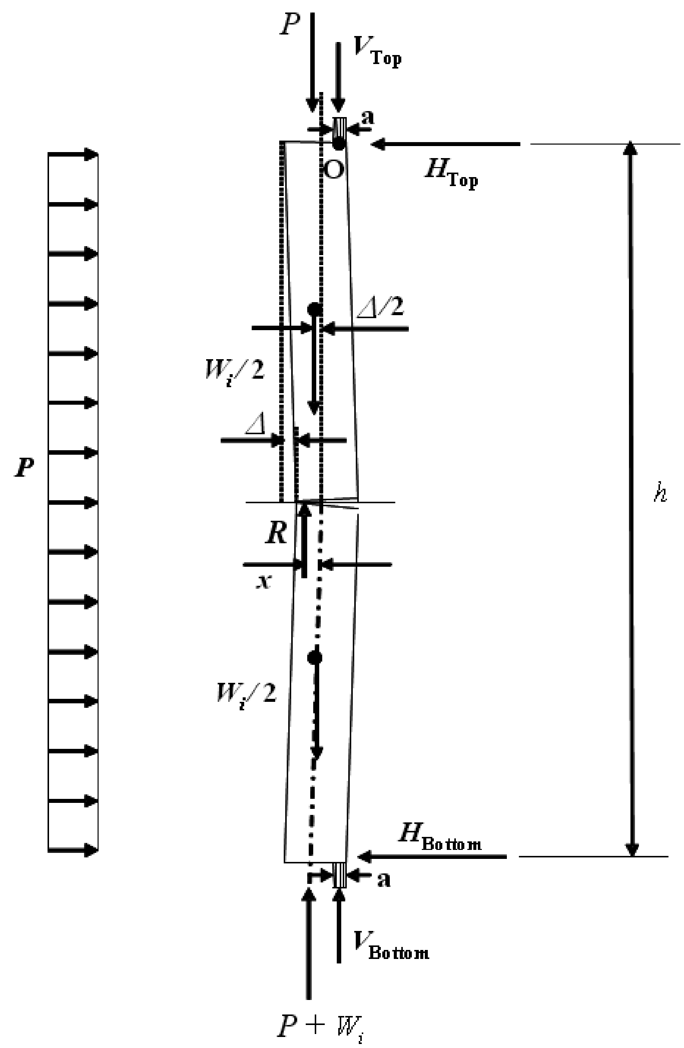

Figure 3. Free-body diagram of the unreinforced concrete masonry wall with arching

$$p = \frac{\left(P + \frac{W_i}{2}\right)\left(\frac{t}{6}\right)}{\left(\frac{h^4}{384E_c I}\right)\left(P + \frac{W_i}{4}\right) + \frac{h^2}{8}} \tag{12}$$

Again it may be assumed that the displacement Δ increases in proportion with the central curvature. Therefore, Eq. (5) holds for this case as well. The wall resistance function in terms of displacement versus lateral load can now be derived in an iterative fashion. At the onset of crack (y = 0), the problem is reduced to two equations (Eqs. (11) and (12)) and two unknowns, Δ and p. As crack grows (y > 0), Δ is calculated using Eq. (5), and p is subsequently calculated using Eq. (9). When this process is programmed for small increments of y, the result defines the resistance of the wall (Figure 4). Figure 4 and all subsequent resistance function plots shown are for:

- Unreinforced concrete masonry wall of 194 mm thickness;
- Concrete masonry hollow blocks with weight of 14.5 kg (142.4 N), volume of 6.01 x 10^6 mm^3, ultimate compressive strength (f'_m) of 13,780 kPa, modulus of elasticity of 13.8 x 10^6 kPa, and Poisson's ratio of 0.15.

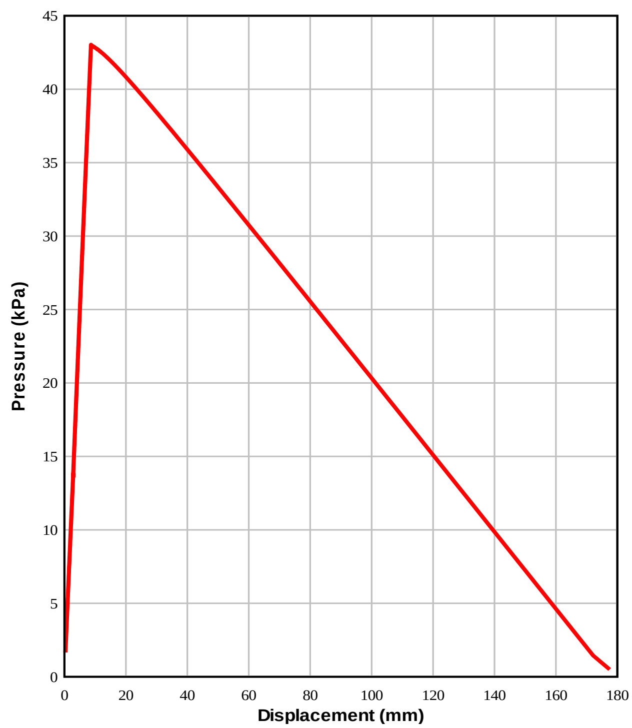

Figure 4. Resistance function – unreinforced CMU wall with arching action

2.3 Resistance Provided by the Catcher Membrane

In this response phase, the displacements are significantly large such that the masonry is fragmented and no longer resists load. Therefore the retrofit acts alone as a tension membrane between the top and bottom supports. Prior to loading, the membrane is in a zero-stress condition but is positioned between

supports without any slack. The pressure is assumed to be uniform along the length of the retrofit, and therefore the membrane is assumed to form a parabolic shape as it deflects; it retains this shape until failure. The length of a parabolic shape may be calculated using the following equation [17]:

$$S = 2\left(\frac{h^2}{16\Delta}\right)\ln\left[4\frac{\Delta}{h}+\sqrt{1+\left(4\frac{\Delta}{h}\right)^2}\right]+\frac{h}{2}\sqrt{1+\left(4\frac{\Delta}{h}\right)^2} \tag{13}$$

This length is used to calculate the strain in the retrofit membrane. Strain is assumed to be uniform throughout the length, and will be used in conjunction with the true stress–strain relationship of the retrofit to obtain the stress. Depending on the material considered and velocity of the response, it may also be necessary to include strain rate effects on mechanical properties. The pressure–deflection relationship can be defined as [18]:

$$p = \frac{8\,\Delta\,t_r\,\sigma}{h^2} \tag{14}$$

Where t_r is the membrane retrofit thickness, σ is the stress in the membrane retrofit material, and all other symbols are as previously defined. A computer program can be set up to calculate the total resistance function, forcing function, lateral displacement, compressive stress, and tensile stresses and strains for each increment of displacement. Figure 5 illustrates a resistance function using a polyurea membrane retrofit, and Figure 6 shows the complete resistance function. The resistance function is truncated for these conditions:

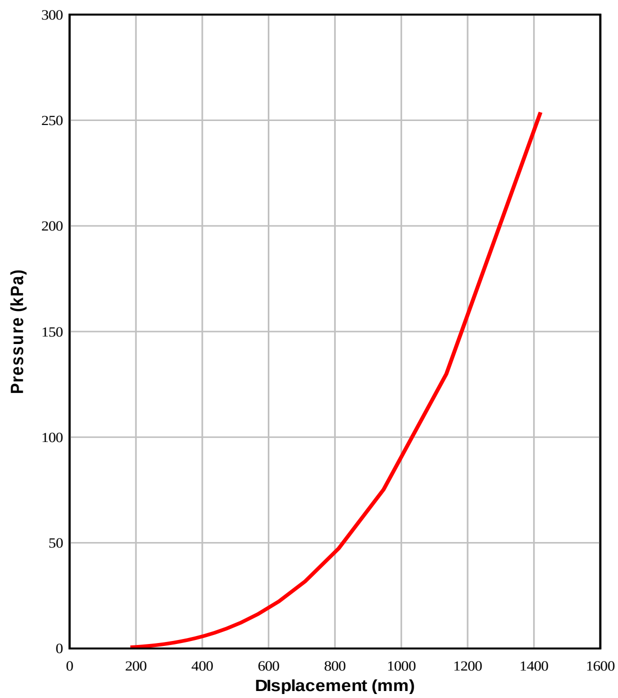

Figure 5. Resistance function — 3 mm thick polyurea retrofit

1. The maximum tensile stresses in the membrane catcher system exceed its ultimate strength
2. The maximum tension or shear at the supports for the membrane catcher system is exceeded
3. Excessive deflection.

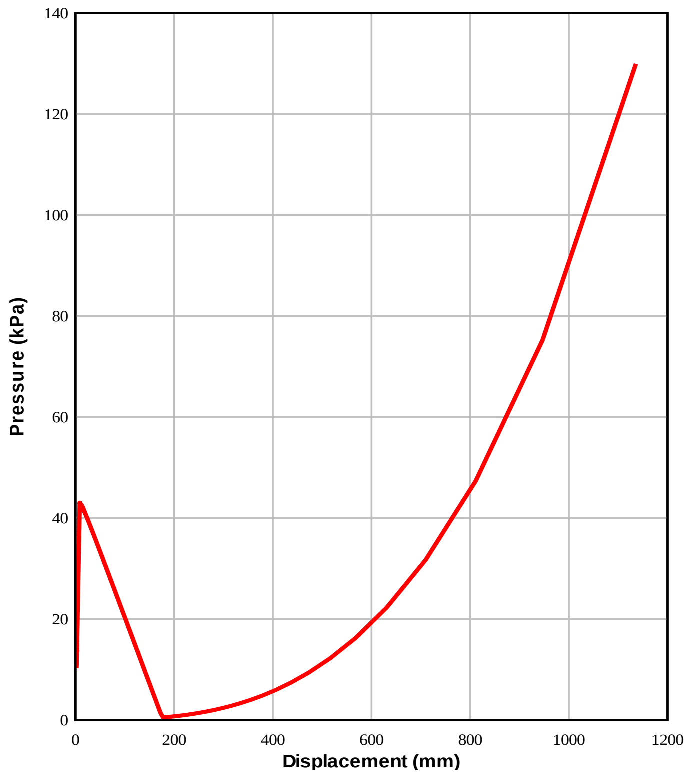

Figure 6. Typical total resistance function of the wall with arching action

3. SINGLE-DEGREE-OF-FREEDOM (SDOF) MODEL DEVELOPMENT

Idealization of the one-way masonry wall as a single-degree-of-freedom (SDOF) system was discussed by Moradi et al. [16], and the solution for the equation of motion was derived. The resulting equation of motion and the difference solution are:

$$M_e \ddot{z}(t) + K_e z(t) = F_e(t) \tag{15}$$

$$z(t+\Delta t) = \frac{F_t \Delta t^2}{K_{LM} M_e} + \left(2 - \frac{R_z \Delta t^2}{K_{LM} M_e}\right) z(t) - z(t-\Delta t) \tag{16}$$

Where M_e is the equivalent mass, K_e is the equivalent stiffness, $F_e(t)$ is the equivalent load–time history applied to the SDOF system, t is the time, Δt is the time interval, z is the displacement, R is the resistance associated with the displacement at time t, and K_{LM} is defined as the ratio of the mass factor to the load factor. The resistance function of the unreinforced concrete masonry wall with membrane catcher system can be used for R_z in Eq. (16) to calculate the wall response to blast loads. Eq. (16) allows for the displacement at the subsequent time increment $z(t+\Delta t)$ to be calculated in terms of

system constants and the current and previous displacement values *z(t)* and *z(t- Δt).* A typical wall response is shown in Figure 7. For this plot and subsequent response plots, a rebound displacement is shown for completeness; however, the formulation presented above was developed to accurately compute the first peak dynamic displacement, but does not necessarily predict the resistance reversal accurately

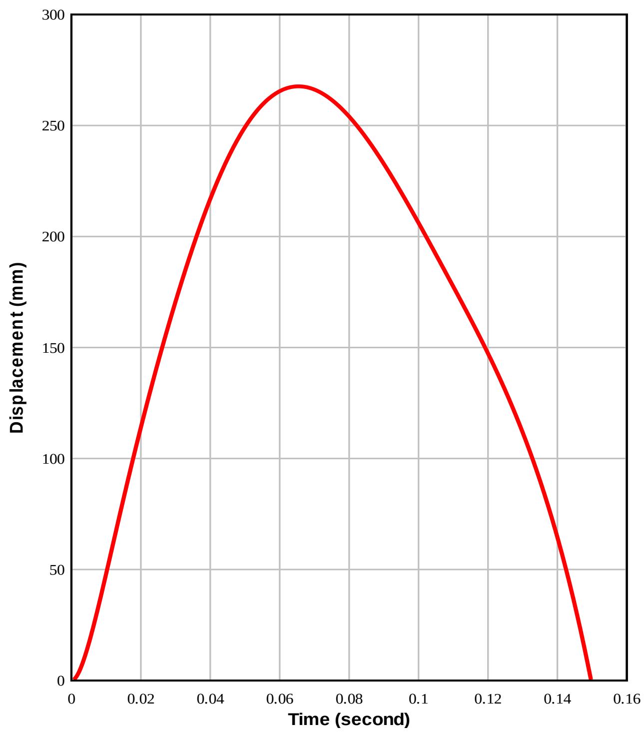

Figure 7. Typical wall response

4. VALIDATION AND DISCUSSION

The catcher system resistance functions were programmed and solved for different wall heights and material property conditions. To demonstrate the accuracy of the methodology, three very disparate membrane retrofit materials were considered. These materials included a soft polymer (E = 234,260 kPa, F_y = 13,780 kPa), a rigid polymeric composite (E = 4.48 x 10^6 kPa, F_y = 29,400 kPa), and a rolled steel (E = 2.07 x 10^8 kPa, F_y = 390,660 kPa). The stress vs. strain properties of the membrane retrofits used in the analyses are shown in Figures 8 through 12. Deflection data resulting from full-scale blast tests, similar to those described by Davidson et al. [5, 6], were used for the validation. The wall height is the unsupported length of the tested wall from the top support to the bottom support. The test wall acts in one-way flexure and resists the incoming blast pressure with simple bending and shear (supported at top and bottom only). The wall dimensions, membrane retrofit type and thickness, and test and SDOF analysis results are summarized in Table 1.

TABLE 1. Comparison of test and analysis results for the catcher system

Wall Test	Retrofit (mm)	*h* (m)	Stress/Strain Properties	Test Max. Deflection (mm)	SDOF Max. Deflection (mm)	% Diff.
1	3 Polyurea Blend	3.66	Figure 8	Collapsed	Collapsed	---
2	3 Polyurea	3.66	Figure 9	Survived Displacement unknown	267	---
3	2 Polymer 1	2.59	Figure 10	286	278	3
4	3 Polyurea	2.59	Figure 9	386	418	7.6
5	3 Polymer 2	2.59	Figure 11	456	452	1
6	None	3.66	---	64	64	0
7	0.6 Sheet Steel	3.05	Figure 12	197	196	0.5

For Test 1, displacement results from both test and SDOF analysis indicate complete collapse of the wall. Displacement results were not available for Test 2 but image data showed that the wall survived. The SDOF analysis shows that the wall survived with a maximum deflection of 267 mm. Displacement results for Tests 3 through 7 show close correlation with the SDOF analysis results, with the largest difference for Test 4 at 7.6%.

The methodology may be used to readily compare wall response for different types of membrane retrofits. To demonstrate this capability, Figure 13 shows the stress–strain properties of three different membrane retrofits; namely steel, polymer 1, and polyurea blend. Thicknesses (0.5 mm, 2 mm, and 3 mm, respectively) were chosen to be representative of membranes that would be used in practice for these specific materials. Figure 14 shows the response of a typical unreinforced concrete masonry wall (3.66 m in height, 194 mm thick) retrofitted with each of these membranes. The wall with the mild steel membrane catcher system deflects nearly 50% less than the same wall with the polymer retrofits. However, even though the stiffer material results in a smaller maximum deflection, it is important to realize that the reaction forces may be much larger than those resulting from the use of softer materials. For example, using the maximum responses illustrated in Figure 14, the support force per length would be 195 kN/m, 29.9 kN/m, and 4.38 kN/m for the steel, polymer 1, and polyurea blend, respectively. Furthermore, on an equivalent displacement limit basis (say 200 mm, which is approximately the thickness of the masonry), the forces would be 205 kN/m, 39.9 kN/m, and 4.74 kN/m for the steel, polymer 1, and polyurea blend, respectively.

Figure 15 shows the typical unreinforced concrete masonry wall 3.66 m high and 194 mm thick retrofitted with 3-mm polyurea blend and exposed to four different levels of impulse pressures. In Figure 16, the same wall is retrofitted with 0.5-mm steel membrane and exposed to the same four impulse pressures. It is noted again that the wall with a steel membrane catcher system deflects signficantly less than the same wall with a polyurea blend catcher system.

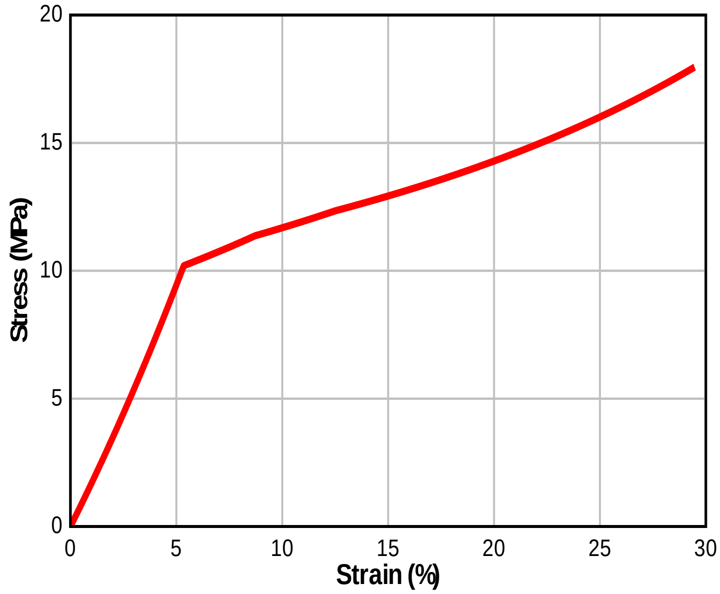

Figure 8. Stress strain properties for polyurea blend

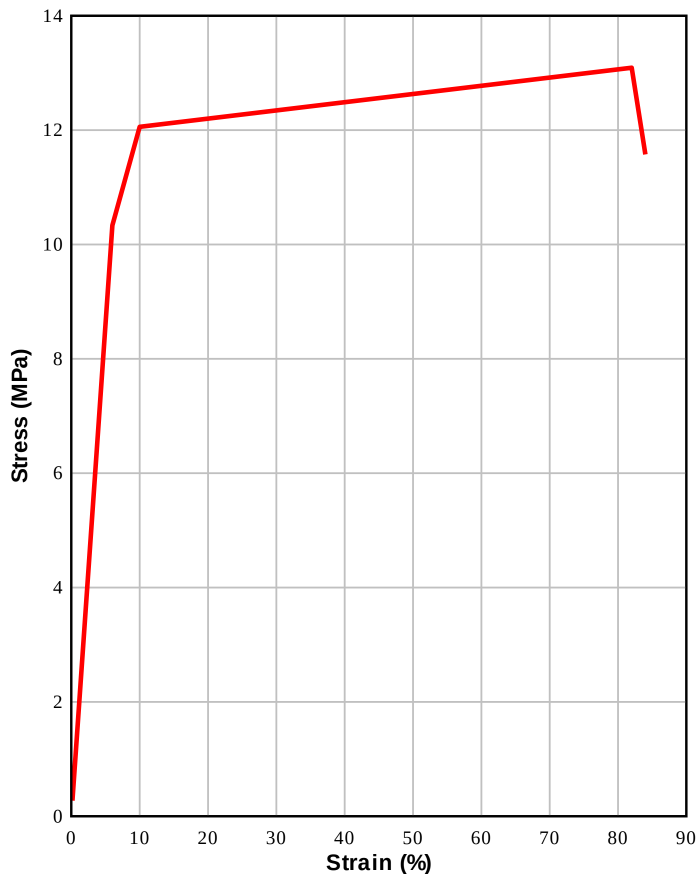

Figure 9. Stress strain properties for polyurea

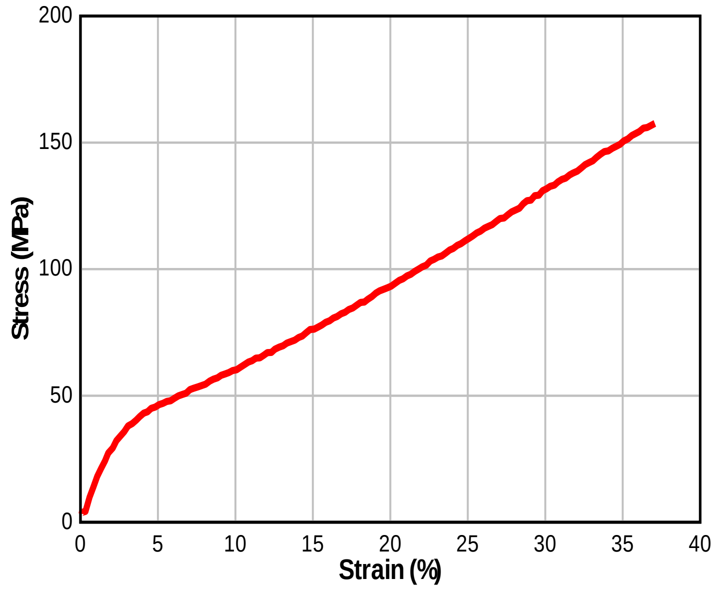

Figure 10. Stress strain properties for polymer 1

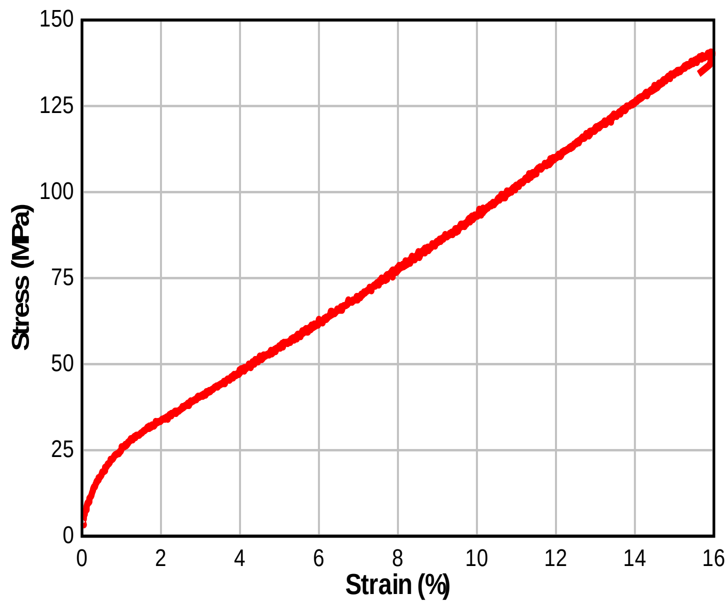

Figure 11. Stress strain properties for polymer 2

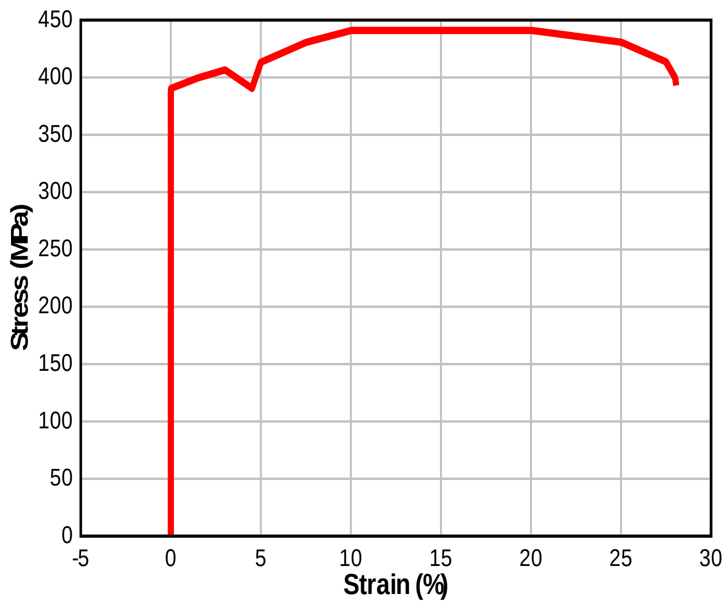

Figure 12. Stress strain properties for Steel membrane retrofit

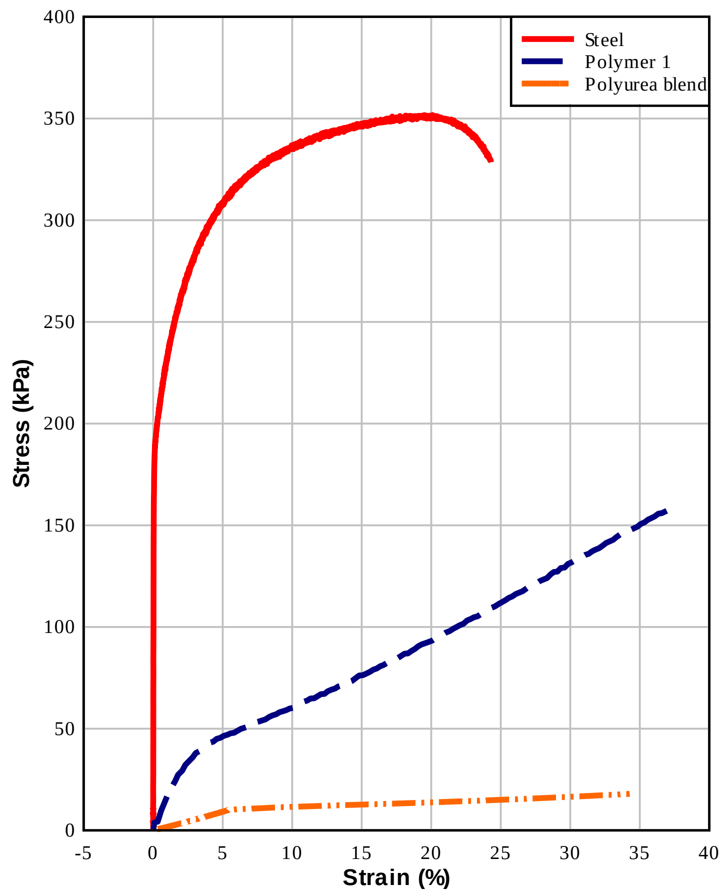

Figure 13. Stress strain properties for three different membrane retrofits

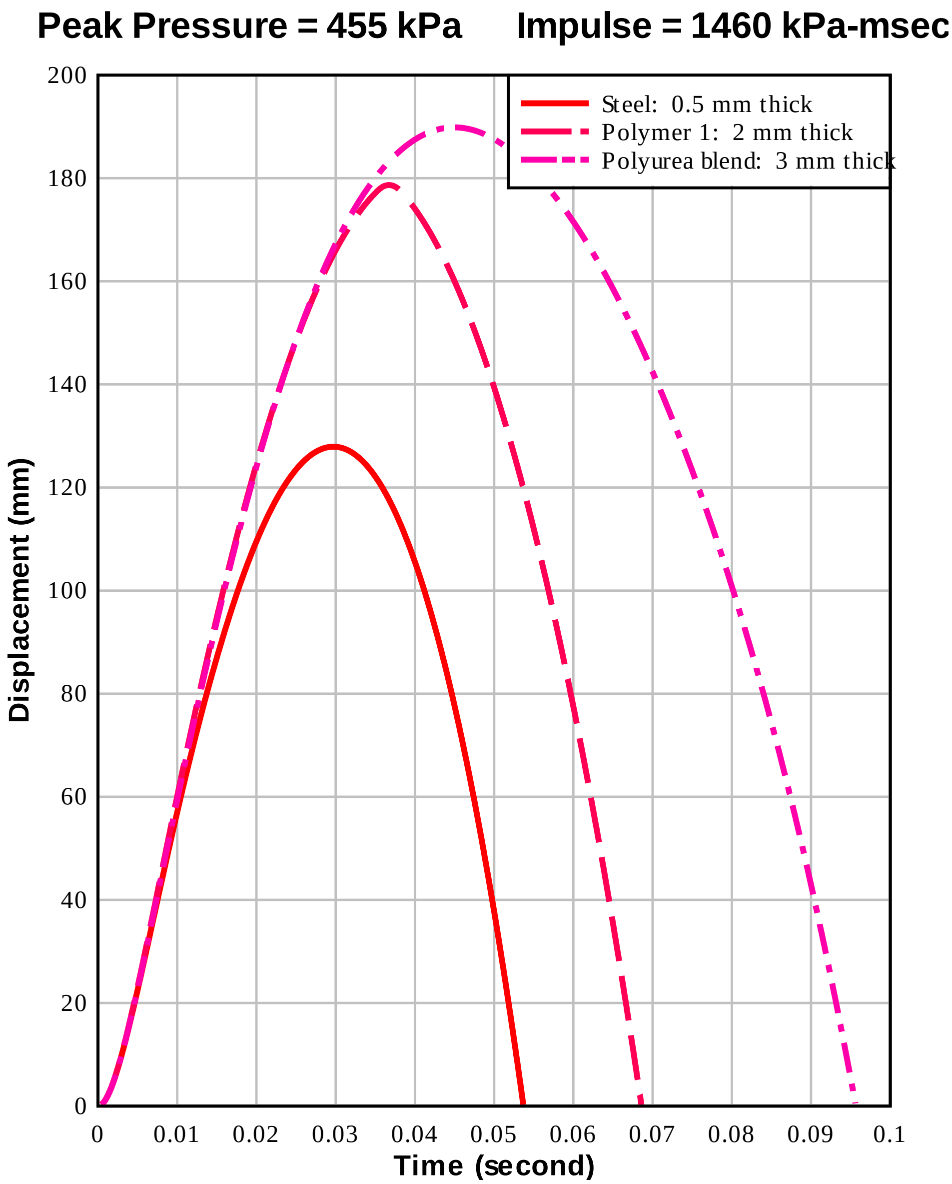

Figure 14. Displacement response for three different membrane retrofits

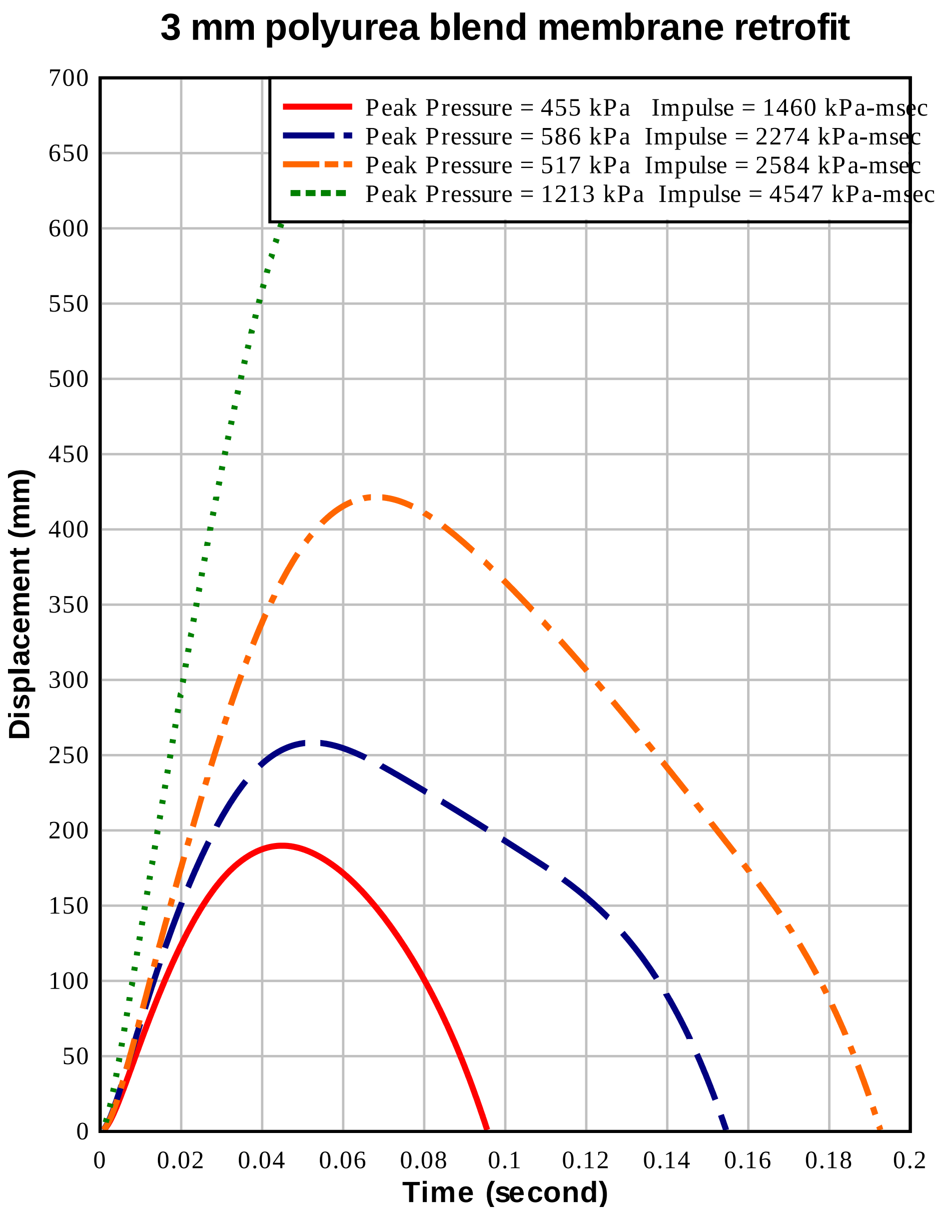

Figure 15. Displacement response of a polyurea blend retrofitted wall with four different impulse pressure events

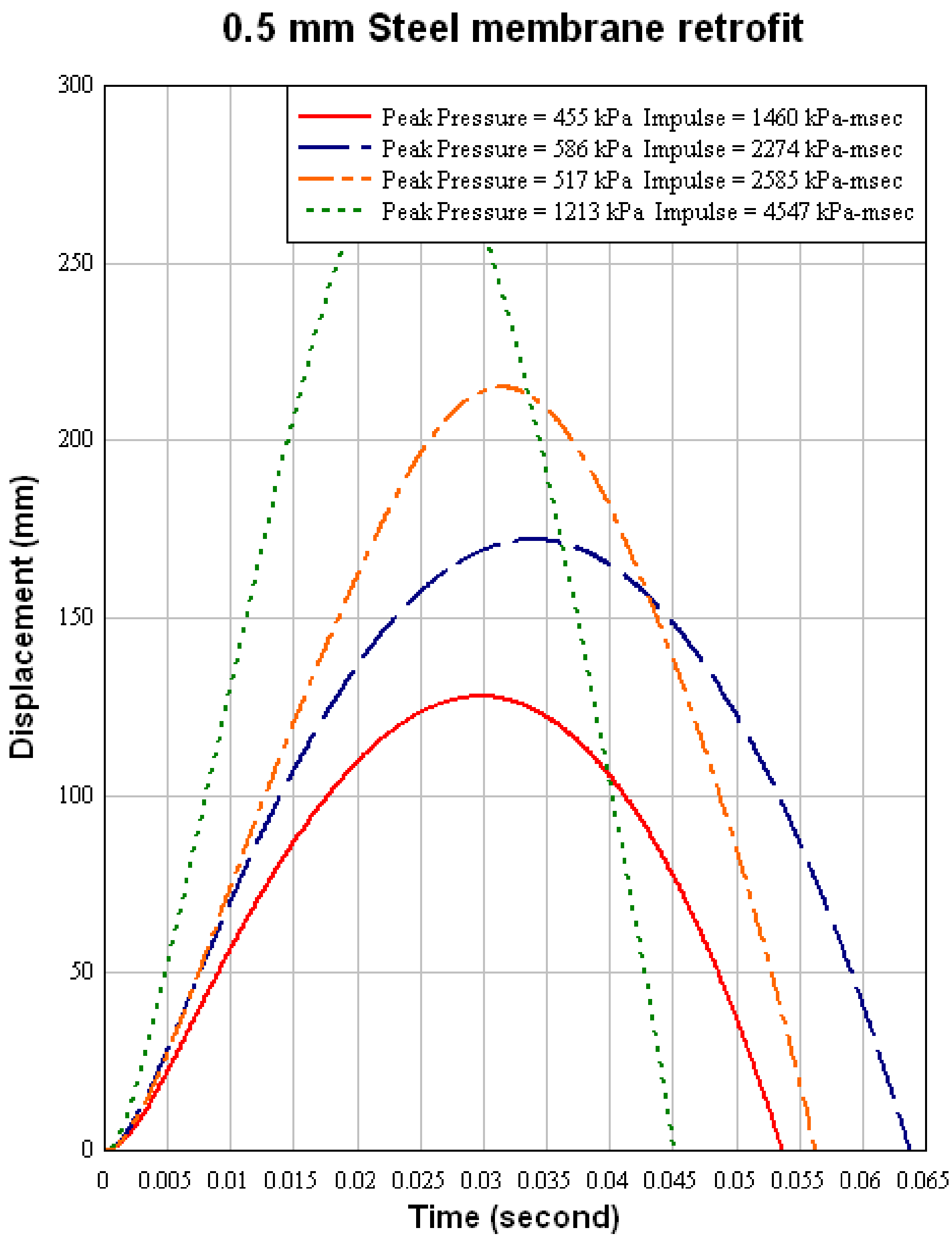

Figure 16. Displacement response of a steel retrofitted wall with four different impulse pressure events

5. CONCLUSIONS AND RECOMMENDATIONS

This paper presents a formulation for the impulse pressure resistance of unreinforced concrete masonry walls that have been retrofitted with membrane catcher systems. The membrane retrofit approach may be used in the construction of new buildings constructed of unreinforced concrete masonry infill walls as well as to retrofit CMU walls of existing buildings. The total resistance function is composed from

two resistance components: (1) the resistance of the one-way CMU wall, with or without arching resistance, and (2) the tension membrane response of the catcher system membrane. For arching action to develop, care must be taken to ensure that gaps are not present between the wall and its top interface. The resistance definition approach presented can easily be programmed into standard SDOF methodology for design and analysis purposes. To demonstrate the accuracy of the methodology, SDOF analyses using three very disparate membrane retrofit materials (a neat polymer, a polymer composite, and steel), were compared to dynamic displacement results from several full-scale explosion tests. Additional data were presented to contrast the response of different materials and under different loadings. The methodology can easily be used to further explore the response advantages of one material over another, and to assess required thickness and connection capacity for a given threat.

Although concrete masonry walls retrofitted with catcher system membranes have demonstrated improved performance under impulse pressure loading, further studies are recommended to quantify and verify the advantages of this approach. Future studies should consider:

a. Connection details and strength at the floor and ceiling levels should be investigated. Adequate extension and attachment of the membrane retrofit through the top and bottom supports play a major role in the structural integrity of the wall system.
b. Static and dynamic tests to better define the strain for the arching ends. To date, little is published on the behavior of the arching ends of the wall system. Knowledge of crushing behavior of the arched end while the wall experiences large deflections is important to the accuracy of the analytical models.

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